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Agronomic and economic response to furrow diking tillage in irrigated and non-irrigated cotton (*Gossypium hirsutum* L.)☆

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ABSTRACT

The Southeast U.S. receives an average of 1300 mm annual rainfall, however poor seasonal distribution of rainfall often limits production. Irrigation is used during the growing season to supplement rainfall to sustain profitable crop production. Increased water capture would improve water use efficiency and reduce irrigation requirements. Furrow diking has been proposed as a cost effective management practice that is designed to create a series of storage basins in the furrow between crop rows to catch and retain rainfall and irrigation water. Furrow diking has received much attention in arid and semi-arid regions with mixed results, yet has not been adapted for cotton production in the Southeast U.S. Our objectives were to evaluate the agronomic response and economic feasibility of producing cotton with and without furrow diking in conventional tillage over a range of irrigation rates including no irrigation. Studies were conducted at two research sites each year from 2005 to 2007. Irrigation scheduling was based on Irrigator Pro for Cotton software. The use of furrow diking in these studies periodically reduced water consumption and improved yield and net returns. In 2006 and 2007, when irrigation scheduling was based on soil water status, an average of 76 mm ha^{-1} of irrigation water was saved by furrow diking, producing similar cotton yield and net returns. Furrow diking improved cotton yield an average of 171 kg ha^{-1} and net return by \$245 ha^{-1} over multiple irrigation rates, in 1 of 3 years. We conclude that furrow diking has the capability to reduce irrigation requirements and the costs associated with irrigation when rainfall is periodic and drought is not severe.

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1. Introduction

Current agricultural water issues and the need for reduced input costs in farming operations add importance to making sound irrigation decisions to ensure efficient use of available resources. Improving water capture and infiltration into the soil may lead to less frequent irrigation, reduce irrigation expenses, and stabilize non-irrigated cropping systems. Current recommendations for reducing runoff and erosion in much of the United States is with reduced tillage methods leaving greater than 30% of the field surface covered with crop residue. Adoption of reduced tillage practices, as of 2004, for Georgia row crop area was about 60% (CTIC, 2004). According to this report, Georgia cotton (*Gossypium hirsutum* L.) growers had adopted reduced tillage practices by nearly 50%, leaving the remainder managed under conventional tillage. According to the 2002 United States Census of Agriculture, 74% of cotton in Georgia was non-irrigated (USDA-NASS, 2002). The majority of economically significant row crops in the United States are grown without irrigation, making the production of these commodities [cotton (61%), peanut (*Arachis hypogea* L.) (62%), and corn (*Zea mays* L.) (86%)] more susceptible to drought conditions and poor yield stability (USDA-NASS, 2002). These statistics suggest that the majority of row crop producers in Georgia and similar states in the Southeast U.S. would benefit by improving water capture and erosion prevention in conventional tillage systems.

Furrow diking is a tillage method that creates a series of basins and dams between crop rows for capturing surface applied water to increase infiltration opportunity time by reducing runoff. Much furrow diking research has been conducted with variations in equipment and terminology including basin tillage, micro-basin tillage, reservoir tillage, furrow blocking, soil pitting, and tied-ridging (Lyle and Dixon, 1977; Hackwell et al., 1991; Unger, 1992; Wiyo et al., 2000; Brhane et al., 2006). Many U.S. patents on furrow diking equipment were issued between 1915 and 1998 (United States Patent Office, 2008). Robert H. McAdams from Abbeville county South Carolina stated in his 1913 application for the 1915 U.S. patent "The object of the present invention is to improve the

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construction of plows, and to provide a simple, efficient and comparatively inexpensive plow designed for the cultivation of cotton, corn and other plants, and equipped with means for automatically lifting a plow proper or furrow opening device to provide a series of reservoirs or furrow sections separated by intervening dams, and adapted to catch and hold the water, which might otherwise run off the ground.'' (United States Patent Office, 2008). This invention is of the raising shovel or wheel type design described by Jones and Stewart (1990) and Harris and Krishna (1989), respectively. It seems, however, that McAdam's contribution was overlooked or discredited during the advancing and development of similar technology. Other literature mentions that furrow diking equipment was first developed during the 1930s in Kansas, Colorado, Nebraska, and Iowa with a similar purpose as McAdam's invention (Lyle and Dixon, 1977; Jones and Stewart, 1990). Lyle and Dixon (1977) further outline the history of the early progress of furrow diking stating that the first commercialized equipment was a result of successful field demonstrations in Kansas, Colorado, and Oklahoma after advances with equipment in 1935. Since this early beginning, many benefits to furrow diking have been recorded in the United States including yield improvement of grain sorghum (*Sorghum bicolor* L.) and cotton (Bilbro and Hudspeth, 1977; Clark, 1983; Gerard et al., 1983, 1984; Jones and Clark, 1987; Tewolde et al., 1993). Irrigation efficiency and reduced precipitation runoff have been documented in furrow diked land compared to non-furrow diked land (Jones and Baumhardt, 2003). Researchers reported successful crop yield improvements and soil conservation benefits from furrow diking experiments in Tanganyika, Nigeria, and Tanzania between 1944 and 1967 (Lyle and Dixon, 1977).

Jones and Stewart (1990) provide a review of furrow diking work and report the range of furrow dike basin depth of water holding capacity to be 25–150 mm, depending on field slope and rainfall intensity. Experiments designed to measure runoff from field surfaces consistently report that furrow diked fields capture more precipitation and/or irrigation than conventionally prepared land (Gerard et al., 1983; Hackwell et al., 1991; Baumhardt et al., 1992; Unger, 1992; Hasheminia, 1994; Truman and Nuti, 2009). Although runoff may be prevented even in fields with minimal slope, furrow diking may provide little benefit for conserving water and improving yield in the arid and semi-arid regions where the majority of furrow diking testing has been done in years with limited overall rainfall (Baumhardt et al., 1993). The Southeast U.S. receives high intensity storms that frequently produce runoff from agricultural fields, however periodic drought is also frequent (Sheridan et al., 1979; Bosch et al., 1999). High intensity storms producing >50 mm are common in the Southeast Coastal Plain (Sheridan et al., 1979; Bosch et al., 1999), thus furrow diking may provide a consistent benefit to row crop producers and reduce the amount of supplemental irrigation used.

The equipment used to install furrow dikes is not expensive and can be attached to conventional equipment making the cost of the practice reasonable (Harris and Krishna, 1989; Jones and Stewart, 1990; Tewolde et al., 1993). Furrow dikes increase field surface area and improve water capture by increasing opportunity time for water percolation (Lyle and Dixon, 1977; Jones and Stewart, 1990) and minimize evaporation of irrigation water (Lyle and Bordovsky, 1983). By permitting higher rates of infiltration, erosion is reduced (Hackwell et al., 1991; Baumhardt et al., 1993; Truman and Nuti, 2009), and water is distributed more uniformly between high and low elevation areas within a field (Hasheminia, 1994). Furrow diking can be used to improve application efficiency of irrigation water (Lyle and Bordovsky, 1983; Hackwell et al., 1991; Hasheminia, 1994) as well as improve the soils' capturing ability of natural precipitation in non-irrigated systems (Jones and Baumhardt, 2003). Non-irrigated crops are more likely affected by erratic rainfall distribution rather than low seasonal rainfall totals (Rathore et al., 1996). To improve efficient use of water in non-irrigated systems, water loss from the soil other than through evapotranspiration such as runoff must be minimized (Rathore et al., 1996). Literature documenting furrow diking in the Southeast U.S. is limited to a single year of research in Alabama using the commercial Dammer Diker (U.S. Patent No. 4508177) (Hackwell et al., 1991) and some Georgia extension experiments conducted in the 1990s evaluating self tripping paddle dikers for peanut production (Bader et al., 1994; Bader and Wilson, 1996). Hackwell et al. (1991) reported that infiltration of irrigation water delivered via low energy precision application was greater with furrow diking and the benefit was more pronounced in compacted soil. Furrow diking irrigated peanut improved pod yield by 135 and 190 kg ha^{-1} in 2 of 3 years (Bader and Wilson, 1996).

Rainfall simulation showed that land without furrow dikes had 3 times more runoff and 3.5 times more erosion compared to land with furrow dikes during a 50 mm rain event (Truman and Nuti, 2009). These results are similar to previous work where the differences in erosion were between 3 and 25 times greater when comparing furrow diking to other practices (Kowal, 1970; Rawitz et al., 1983). Furrow diking limited runoff to 17% of the total water applied compared to land without furrow dikes (53% runoff) (Truman and Nuti, 2009).

Both irrigated and non-irrigated cropping systems may benefit from furrow diking by improved water capture and water use efficiency. Field studies were established with the following objectives: (1) relate furrow diking to seasonal crop water use when irrigation scheduling is based on a computerized decision support system, (2) determine the degree that furrow diking affects cotton yield with (2a) variable irrigation rates including (2b) non-irrigated systems, and (3) compare the economic returns of furrow diking to conventional tillage without furrow diking.

2. Materials and methods

2.1. Experimental sites

Research was conducted between 2005 and 2007 at two irrigation research farms managed by USDA-ARS-NPRL. Two separate field studies with individual objectives were managed independently at these locations. The soil type at Dawson, Georgia was Tifton (Fine-loamy, kaolinitic, thermic Plinthic Kandiudults; 0–2% slope) and the soil type at Shellman, Georgia was Greenville (Fine, kaolinitic, thermic Rhodic Kandiudults; 0–2% slope). Objective 1 and 2b are addressed by the project at Dawson, objective 2a is addressed by the project at Shellman, and economic analysis was performed on treatments at both locations to address objective 3.

2.2. Crop management and description of equipment

Both research sites were managed with conventional tillage consisting of disking the previous crop stubble, and planting a winter rye (*Secale cereale* L.) or wheat (*Triticum aestivum* L.) cover crop. Each spring, the cover crop was disked and field cultivated. All plots were prepared with a ripper–bedder that subsoiled >0.4 m deep. In furrow-diked treatments, furrow diking was conducted after cotton seedlings emerged. Furrow diking requires loose soil for creating the dams and basins, so this is commonly done in combination with a cultivator (Cooper, 1971; Lyle and Dixon, 1977). The two paddle self-tripping furrow dikers used in the present study create furrow dikes that are approximately 1.5 m long, 0.30 m wide, and 0.2 m deep (Fig. 1). These units were pulled in conjunction with a two-row Brown Chiselvator (Brown Manufacturing Company, Ozark, Alabama) (Fig. 1). The Brown

Fig. 1. A two-paddle furrow diking unit attached to a Brown Chiselvator (inset). Ripper shanks run in front of cultivator sweeps and the furrow diking attachment creates a series of depressional storage basins with the loosened soil as demonstrated in the background.

Chiselvator is a heavy cultivator that includes a ripper shank made of 16 mm × 105 mm steel and measures 0.45 m from the tip to a point parallel to the back of the shank. In these studies, the ripper shank was used at a depth of 0.2 m in every row middle of furrow-diked treatments. In furrow-diked treatments, furrow dikes were created in every other row, leaving traffic rows non-diked (Lyle and Dixon, 1977; Jones and Stewart, 1990). Crop management for soil nutrients, pest control, and harvest aid application was in accordance with best management practices for Southeast cotton production.

2.3. Measurements and experimental design

The objectives of the irrigation scheduling × furrow diking study in Dawson were to determine if furrow diking could affect soil water potential and net return values at agronomically significant levels in both irrigated and non-irrigated cotton. Irrigation scheduling in cotton was dictated by decision support software (Irrigator Pro for Cotton version 2.0 in 2005 and 2006 and version 2.0.2 in 2007). The Irrigator Pro for Cotton software program is for managing irrigation scheduling in cotton and was developed and released by the USDA-ARS-NPRL in collaboration with the University of Georgia (Davidson et al., 1998). There are separate Irrigator Pro models for peanut, cotton, and corn. The model is designed to avoid crop stress while triggering irrigation at the most efficient timing and volume to avoid over-irrigation. Data required for Irrigator Pro for Cotton includes soil type, planting date, daily rainfall and irrigation amounts, and cotton growth stages including first square, first open bloom, and first cracked boll. Irrigator Pro for Cotton uses estimated daily crop water use in accordance with established base values within various growth stages (Brown et al., 2008). Daily soil water potential at 0.2, 0.4, and 0.6 m is entered in the program. A weighted system is used to average soil water potential over the three depths where the most shallow sensor carries 43% of the average compared to 32% at 0.4 m and 25% at 0.6 m. An average soil water potential of −50 kPa will trigger irrigation. Soil water potential (Watermark soil moisture sensor, Irrometer; Riverside, California) at 0.2, 0.4, and 0.6 m depths was recorded in 15 min intervals throughout the season (CR-23X datalogger, Campbell Scientific; Logan, Utah). Soil water potential was corrected using a common 50 mm soil temperature recorded at 04:00 daily. Soil monitoring equipment was placed in line with the crop row and was measured in three replications of each treatment. A factorial treatment design was used including irrigated, non-irrigated, furrow diked, and non-furrow-diked treatments. Treatments appeared in a split-plot field design with irrigation as main plots and furrow diking as sub-plots. Sub-plots were 5.5 m wide and 15.2 m long. Each plot had six 0.91 m wide rows and data were collected from the middle two rows. Ten border rows were between each of the six-row plots in order to reduce border effects and potential run-on or runoff from adjacent plots. Each treatment combination was replicated four times. Irrigation was managed separately by furrow diking as dictated by Irrigator Pro for Cotton. Irrigation was provided through a lateral move overhead irrigation system equipped with spray nozzles on drops 2.5 m above the ground. Irrigation, rainfall, and total water applied at Dawson are listed in Table 1. Cotton cultivar 'DP 451 B/RR' (Delta and Pine Land Company; Scott, Mississippi) was planted in 2005 and cultivar 'DP 455 B/RR' was used in 2006 and 2007. Cotton was planted 18 May 2005, 4 May 2006, and 1 May 2007.

The objectives of the irrigation rate × furrow diking study in Shellman were to determine if furrow diking could affect cotton yield response and net return values over a range of irrigation rates. This study was part of a larger crop rotation study, where cotton appeared twice in 2005, once in 2006, and three times in 2007. Irrigation rate and timing were dictated by Irrigator Pro for Cotton based on a full irrigation (100%) treatment. Treatments consisted of a factorial design of furrow diked and non-furrow-diked tillage over four irrigation rates. Irrigation rate was the main plot factor and furrow diking was assigned to sub-plots within irrigation rate. Sub-plots were 7.3 m × 30.5 m. Irrigation rates were 100, 66, 33, and 0% of the amount recommended by Irrigator Pro for Cotton. Each treatment combination was replicated three times. A three-span lateral irrigation system was utilized with each span delivering the prescribed irrigation rate. The first span delivered the full amount (100%); the second and third spans had more restrictive nozzles to achieve the 66 and 33% rates. The non-irrigated treatments were arranged in plots located beyond the end of the irrigation system. Irrigation was applied to all plots at respective rates at the same time. Since the objective was to determine if furrow diking could improve the efficiency of an existing system, irrigation was based on the water demand of non-diked plots managed for full yield potential without stress (100%). Irrigation, rainfall, and total water applied to the crop for the irrigation rate × furrow diking study are listed in Table 2. Cotton cultivar 'DP 555 B/RR' was planted between 20 and 25 May in 2005 to 2007.

Table 1
Seasonal rain accumulation and irrigation totals for irrigated cotton research in Dawson, Georgia.

Year and tillage	Rain events (no.)	Rainfall[a] (mm)	Irrigation[b] (mm)	Rainfall + irrigation (mm)
2005 furrow diked	38	533	25	558
2005 non-diked	38	533	25	558
2006 furrow diked	17	305	248	553
2006 non-diked	17	305	273	578
2007 furrow diked	16	198	584	782
2007 non-diked	16	198	711	909

[a] Reported rainfall totals are the accumulation from planting to crop termination.
[b] Irrigation rate and timing were dictated by Irrigator Pro for Cotton.

Table 2
Seasonal rain accumulation and irrigation totals for irrigated cotton research in Shellman, Georgia.

Year	Irrigation rate (%)	Rain events (no.)	Rainfall[a] (mm)	Irrigation[b] (mm)	Rainfall + irrigation (mm)
2005	100	23	498	76	574
2005	66	23	498	51	549
2005	33	23	498	25	523
2005	0	23	498	0	498
2006	100	29	414	457	871
2006	66	29	414	305	719
2006	33	29	414	152	566
2006	0	29	414	0	414
2007	100	20	269	432	701
2007	66	20	269	287	556
2007	33	20	269	145	414
2007	0	20	269	0	269

[a] Reported rainfall totals are the accumulation from planting to crop termination.
[b] Irrigation rate and timing were dictated by Irrigator Pro for Cotton.

In each study, cotton was machine picked from the middle two rows for the full length of each sub-plot and a sub-sample (200 g) of seedcotton was ginned. Lint yield was used to calculate crop value at \$1.551 kg^{-1}. Irrigation costs were calculated considering that the energy required for applying 10 mm of water ha^{-1} was \$11.67. The labor and fuel required to run furrow diking equipment was \$20 ha^{-1}. The term crop water use in this manuscript refers to the economically measurable water applied through the irrigation systems used to produce the crop. The use of this term should not be confused with other terms such as plant water use efficiency or evapotranspiration. The estimates included in the Irrigator Pro for Cotton software model are assumed to be appropriate and the efficiencies of the irrigation systems are assumed to be equal among replications within the same study. Net returns were calculated assuming the production costs between treatments other than irrigation and furrow diking were equal. For the purposes of these studies, other production costs are not reflected in the net return values and are assumed to be equal among treatments.

Data for each of these studies were combined over years and analyzed in SAS (version 9.1) under the general linear model and means were separated using Fisher's Protected LSD at $\alpha \leq 0.05$. At Shellman, crop rotation was not significant and was removed from the statistical model to achieve greater replication. A significant year × irrigation interaction was present for yield and net return in each study, so data were analyzed separately by year. The irrigation × furrow diking interaction was not significant in individual years, thus results are reported combined over main effects.

3. Results and discussion

3.1. Dawson (irrigation scheduling × furrow diking)

The annual variability in rainfall and irrigation costs resulted in a significant year × irrigation interaction for yield and net return at Dawson. The irrigation main effect on yield and net return is reported separately by year (Table 3). Cotton yield ranged from 1384 to 1392 kg ha^{-1} in 2005 and was not affected by irrigation. Rainfall was plentiful and irrigation was required only once for the irrigated treatments; consequently, irrigation did not positively affect yield in 2005. Net return ranged between \$2120 and \$2136 ha^{-1} for irrigated and non-irrigated cotton, respectively, in 2005. Irrigated cotton produced an average of 201 kg ha^{-1} more lint than non-irrigated cotton in 2006, however the margin of crop value accounted for by yield improvement from irrigation (\$312 ha^{-1}) did not exceed the irrigation costs (\$314 ha^{-1}). Irrigation requirements were greatest in 2007 (Table 1), resulting in the highest annual yield for irrigated cotton at Dawson averaging 2210 kg ha^{-1} (Table 3). Irrigation in 2007 was greater than 2 fold the amount used in 2006, costing \$766 ha^{-1}. The drought of 2007 provided the climate for a significant improvement in net return associated with irrigation of \$1572 ha^{-1}.

The furrow diking main effect on yield and net return is reported separately by year (Table 4). In 2005, when precipitation was sufficient and cotton yield was not affected by irrigation, yield and net return were not affected by furrow diking. Similar results were found by McFarland et al. (1991) where corn yield was not affected by furrow diking when average or above average rainfall

Table 3
Effect of irrigation on cotton yield and net return in Dawson, Georgia.

Treatment	2005				2006				2007			
	Lint yield (kg ha^{-1})	Trt. cost (\$ ha^{-1})	Crop value (\$ ha^{-1})	Net return (\$ ha^{-1})	Lint yield (kg ha^{-1})	Trt. cost (\$ ha^{-1})	Crop value (\$ ha^{-1})	Net return (\$ ha^{-1})	Lint yield (kg ha^{-1})	Trt. cost (\$ ha^{-1})	Crop value (\$ ha^{-1})	Net return (\$ ha^{-1})
Irrigated	1392 A[a]	40	2160	2120 A	1118 A	314	1734	1420 A	2210 A	766	3428	2662 A
Non-irrigated	1384 A	10	2146	2136 A	917 B	10	1422	1412 A	710 B	10	1100	1090 B

[a] Means in a column followed by the same letter are not statistically different according to Fisher's Protected LSD at α = 0.05.

Table 4
Effect of furrow diking on cotton yield and net return in Dawson, Georgia.

Treatment	2005				2006				2007			
	Lint yield (kg ha^{-1})	Trt. cost (\$ ha^{-1})	Crop value (\$ ha^{-1})	Net return (\$ ha^{-1})	Lint yield (kg ha^{-1})	Trt. cost (\$ ha^{-1})	Crop value (\$ ha^{-1})	Net return (\$ ha^{-1})	Lint yield (kg ha^{-1})	Trt. cost (\$ ha^{-1})	Crop value (\$ ha^{-1})	Net return (\$ ha^{-1})
Furrow diked	1398 A[a]	35	2168	2133 A	1018 A	165	1579	1414 A	1476 A	361	2288	1927 A
Non-furrow diked	1378 A	15	2138	2123 A	1017 A	160	1577	1417 A	1445 A	415	2240	1825 A

[a] Means in a column followed by the same letter are not statistically different according to Fisher's Protected LSD at α = 0.05.

Table 5
Irrigation and rainfall during the period between 30 June 2007 and 17 July 2007 for irrigated cotton research in Dawson, Georgia.

Date	Irrigation[a] (mm)		Rainfall (mm)	Rainfall + irrigation (mm)	
	Furrow diked	Non-diked		Furrow diked	Non-diked
30 June	0	0	0	0	0
1 July	0	0	5	5	5
2 July	0	0	0	0	0
3 July	25	25	0	25	25
4 July	0	0	0	0	0
5 July	25	25	0	25	25
6 July	0	25	5	5	30
7 July	25	0	15	40	15
8 July	0	0	0	0	0
9 July	0	0	15	15	15
10 July	0	0	0	0	0
11 July	0	0	0	0	0
12 July	0	25	0	0	25
13 July	0	0	18	18	18
14 July	0	0	0	0	0
15 July	0	0	0	0	0
16 July	25	0	0	25	0
17 July	0	25	0	0	25
Total water applied during the period[b]				158	183

[a] Irrigation rate and timing were dictated by Irrigator Pro for Cotton.
[b] This 18 day period illustrates how irrigation demand was reduced in furrow-diked cotton by more efficient capture of both rainfall and irrigation. Situations similar to this period occurred once in 2006 and five times in 2007.

was received. In 2006 and 2007, greater amounts of irrigation were required because of drought; however furrow diking did not affect cotton yield or net return in these years at Dawson. Nonetheless, furrow diking did affect irrigation scheduling within the irrigated treatments, and consequently reduced supplemental water requirements. In 2006 and 2007, irrigated non-furrow-diked plots required 25 mm ha^{-1} (one event) and 127 mm ha^{-1} (five events) more irrigation water, respectively compared to furrow-diked plots irrigated according to recommendations from Irrigator Pro for Cotton, which is driven by soil water measurements used by the model in the software. The apparent difference in water capture of furrow-diked plots associated with timely rain events allowed the situation where irrigation intervals overlapped to effectively reduce supplemental irrigation requirements as demonstrated in Table 5. Table 5 shows daily irrigation and rainfall for furrow diked and non-furrow-diked treatments during an 18-day period in the irrigation scheduling study at Dawson in 2007. Rainfall accumulation was 35 mm during the period between 6 July and 9 July 2007. More efficient capture of rainfall and irrigation water resulted in reducing irrigation required in the furrow-diked treatment during the period between 30 June and 17 July. Water use during the period shown in Table 5 was equal between treatments through 5 July. Water use between 6 July and 13 July was 78 and 103 mm, respectively, for the furrow diked and non-furrow-diked treatments. Similar situations to this occurred in 2006 and 2007 for the respective annual reduced water consumption of 25 and 127 mm ha^{-1} in Dawson. The fact that the furrow-diked treatment required the fourth irrigation within 1 day of the non-furrow-diked treatment requiring the fifth irrigation during the period shown in Table 5 demonstrates the difference in water use efficiency between furrow diking treatments (16%) due to greater water capturing ability compared to conventionally tilled treatments without furrow diking (Baumhardt et al., 1992, 1993).

Results of rainfall simulation experiments show that, a 50 mm rain event supplied 7.0 days of plant available water on furrow diked land compared to 3.8 days on land without furrow dikes (Truman and Nuti, 2009). The goal of the irrigation scheduling software program is to supply water to the soil in a manner that will maintain soil water at levels sufficient to avoid plant stress without over application. These results are agronomically significant because irrigation recommendations in this study were fewer in furrow-diked plots and there was no significant sacrifice of yield or net return by following the recommendations. Irrigation requirements are an indirect result of water capture and soil water potential measurements. Truman and Nuti (2009) found that water capture was greater with furrow diking compared to conventional tillage documenting a 36% change in runoff. One may assume that if the water did not runoff, it either infiltrated or evaporated. Results similar to these are supported by Gerard et al. (1983), Hackwell et al. (1991), Baumhardt et al. (1992), Unger (1992), and Hasheminia (1994).

3.2. Shellman (irrigation rate × furrow diking study)

This study was part of a larger crop rotation study including cotton, corn, and peanuts. Crop rotation had no significant effect on cotton response to the main effects of irrigation rate or furrow diking, so crop rotation was removed from the statistical model and used to achieve greater replication in 2005 and 2007. In 2006, cotton appeared in only one crop rotation. The interactions for year × irrigation and year × furrow diking were significant, so data were analyzed separately by year. The significant year × furrow diking interaction shows that cotton grown under a range of irrigation management regimes responded differently to furrow diking. This was most likely a response to the variable rainfall and irrigation requirements during these studies (Table 2).

In 2005, rainfall was plentiful, requiring limited irrigation. Irrigation improved cotton yield by an average of 282 kg ha^{-1} compared to non-irrigated treatments in 2005 (Table 6). Net return of irrigated cotton in 2005 averaged \$378 ha^{-1} more than non-irrigated cotton. As irrigation rate increased, cotton yield significantly improved between rates in 2006. Irrigation improved net return over non-irrigated cotton by \$910 ha^{-1} in 2006. In 2007, non-irrigated cotton yield was 402 kg ha^{-1} compared to 819 kg ha^{-1} at the 33% irrigation rate. Irrigation at the 100 and 66% rates produced similar cotton yield in 2007 averaging 1675 kg ha^{-1} which was more than 2-fold greater than the yield of cotton irrigated with the 33% rate that year. Cotton irrigated at the full recommended rate produced similar net return compared to cotton irrigated at the 66% rate in 2006 and 2007. These results

Table 6
Effect of irrigation rate pooled over furrow diking on cotton yield in Shellman, Georgia.

Treatment	2005				2006				2007			
	Lint yield (kg ha^{-1})	Trt. cost (\$ ha^{-1})	Crop value (\$ ha^{-1})	Net return (\$ ha^{-1})	Lint yield (kg ha^{-1})	Trt. cost (\$ ha^{-1})	Crop value (\$ ha^{-1})	Net return (\$ ha^{-1})	Lint yield (kg ha^{-1})	Trt. cost (\$ ha^{-1})	Crop value (\$ ha^{-1})	Net return (\$ ha^{-1})
Irrigated 100%	1445 A[a]	99	2241	2142 A	1617 A	541	2508	1967 A	1703 A	513	2642	2129 A
Irrigated 66%	1382 A	69	2143	2074 A	1466 B	364	2273	1909 A	1646 A	345	2554	2209 A
Irrigated 33%	1341 A	40	2080	2040 A	1085 C	187	1683	1496 B	819 B	178	1271	1093 B
Non-irrigated	1107 B	10	1717	1707 B	574 D	10	891	881 C	402 C	10	623	613 C

[a] Means in a column followed by the same letter are not statistically different according to Fisher's Protected LSD at α = 0.05.

Table 7
Effect of furrow diking pooled over irrigation rate on cotton yield in Shellman, Georgia.

Treatment	2005				2006				2007			
	Lint yield (kg ha^{-1})	Trt. cost ($ ha^{-1})	Crop value ($ ha^{-1})	Net return ($ ha^{-1})	Lint yield (kg ha^{-1})	Trt. cost ($ ha^{-1})	Crop value ($ ha^{-1})	Net return ($ ha^{-1})	Lint yield (kg ha^{-1})	Trt. cost ($ ha^{-1})	Crop value ($ ha^{-1})	Net return ($ ha^{-1})
Furrow diked	1308 A[a]	65	2029	1964 A	1271 A	286	1971	1685 A	1143 A	272	1773	1501 A
Non-furrow diked	1329 A	45	2061	2016 A	1100 B	266	1706	1440 B	1093 A	252	1695	1443 A

[a] Means in a column followed by the same letter are not statistically different according to Fisher's Protected LSD at $\alpha = 0$.

show that at the economic costs and values used in this study, the full irrigation rate did not improve net return over the 66% rate in all 3 years.

The main effect of furrow diking for yield and net return was not significant in both an above average (2005) and below average (2007) rainfall year (Table 7). This was similar to other studies where limited water was available and furrow diking had no positive affect on yield (Baumhardt et al., 1993). The yield range between furrow diking treatments was 1308–1329 kg ha^{-1} in 2005 and 1143–1093 kg ha^{-1} in 2007. Furrow diking significantly improved yield in 2006 by 171 kg ha^{-1} compared to non-furrow-diked treatments (1100 vs. 1271 kg ha^{-1}). Clark (1983) and Gerard et al. (1984) also reported positive cotton yield increases with furrow diking. Net return was significantly improved in 2006 by $245 ha^{-1} over all irrigation rates with furrow diking. The within irrigation rate effect of furrow diking was greater at the lower irrigation rates. In 2006, the numerical separation between means due to furrow diking was 258 (58%), 268 (28%), 144 (10%), and 14 (1%) kg ha^{-1}, respectively for the non-irrigated, 33, 66, and 100% irrigation rates.

4. Summary and conclusions

Overall, yield and net return were not affected by furrow diking in the irrigation scheduling study at Dawson, but irrigation demand was reduced in 2 of 3 years by furrow diking. Furrow diking improved cotton yield (171 kg ha^{-1}) and net return ($245 ha^{-1}) in 1 of 3 years (2006) in the irrigation rate study at Shellman. Although the instance of positive results of this practice was limited in these studies, negative yield and net return was not observed. The economic results of the irrigation rate study at Shellman suggest that furrow diking may contribute to economic stability, through water conservation and reduced inputs, for cotton production in the Southeast U.S. Considering the cost for furrow diking ($20 ha^{-1}) and the significant net return ($245 ha^{-1}) in 1 of 3 years, the positive net returns of one year would cover the cost of the practice for 12 years. The cost for furrow diking in the years without a significant yield or net return is easily made up by the difference in 2006, when the furrow diking practice returned more than was spent, and the excess was enough to pay for the practice in the years with no yield improvement or irrigation savings. These conclusions do not encompass the environmental benefits of furrow diking which are threefold and further explained in a complimentary manuscript (Truman and Nuti, 2009). Most evident and measurable is the great magnitude of erosion prevention during high intensity rain events (Shipitalo and Owens, 2006). The second factor is reduced consumption of fresh water resources. If a conservation method such as furrow diking was widely adopted in the Southeast U.S., current production levels could be maintained at a more sustainable level and water resources could be available for other needs. Finally, the fossil fuels required for energy production saved by reducing irrigation requirements would be available for future generations and could positively affect current pollution levels. As was demonstrated by the irrigation scheduling study in 2006, irrigation significantly improved yield, but it did not improve net return. This means that irrigation was unnecessary in 2005 and 2006 to produce the best economic yield. The variability in rainfall and energy costs between years, does not allow us to conclude that irrigation is not necessary, because irrigation increased overall net return by $1571 ha^{-1} in 2007. The response to irrigation in 2007 demonstrates that irrigation is necessary to provide economic stability in the Southeast U.S. by supplementing rainfall during drought.

The significant interaction of furrow diking over years as observed in the irrigation rate study suggests that there must be water (rainfall or irrigation) available to capture, and there must be a stressful environment causing measurable reduction in plant growth that can be alleviated by the differential amount of water captured and supplied to the soil by furrow dikes compared to non-diked management. Harris and Krishna (1989) state that crop yields may be improved by the small amounts of water made available to the crop by furrow diking. If rainfall sufficiently supplies the crop, and little irrigation is used, efficiency in water capture is not as important. In years with high rainfall, erosion is more of a concern and furrow diking has a great positive effect on reducing erosion (Gerard et al., 1983; Hackwell et al., 1991; Baumhardt et al., 1992; Unger, 1992; Hasheminia, 1994; Truman and Nuti, 2009), so this tillage system has beneficial aspects in multiple environments regularly occurring in the Southeast U.S. Some of the greatest net returns were associated with the low irrigation requirements of 2005. The highest yields were attained in 2007, however the irrigation costs reduced net returns to levels comparable to those made in 2005. Furrow diking had significantly positive yield and net returns in the 2006 irrigation rate study, because the intermediate drought conditions coupled with improved water capture by furrow diking provided the stressful environment with the improved soil water supply needed for cotton to show a response over a range of irrigation rates. This technology is suitable for these conditions by providing stability to existing systems by making them more efficient and should not cause adverse effects on farm income (Tewolde et al., 1993).

Furrow diking in these studies was done with two-row equipment, creating furrow dikes in every other row. It is conceivable that growers choosing to adopt this technology would use larger equipment requiring fewer traffic rows and would be able to dike a greater percent of rows. For example six-row equipment would allow diking four rows and leave two rows for traffic as is suggested by Jones and Stewart (1990). This suggests that their practice would have a higher potential for water capture and erosion prevention compared to that found in this study simply by furrow diking a greater percentage of rows.

Although positive results were observed in both experiments, positive yield and net returns associated with furrow diking were only present in 1 of 3 years in 1 of 2 experiments. Net irrigation was reduced by 25 and 127 mm ha^{-1} in 2006 and 2007 with furrow diking without sacrificing yield or net return.

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